BLIND SEPARATION OF CONVOLVED MIXTURES FOR CDMA SYSTEMS

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ABSTRACT

This paper presents a new method for symbol estimation in the downlink of a CDMA communication system. Our approach is based on the observation that the slowly-fading CDMA signal model may be expressed as a linear combination of the convolved independent symbol sequences. A blind source separation approach based on maximization of output entropy is used for the blind separation of the sources; the symbols corresponding to the user of interest are determined using a small training sequence. Our method shows good simulation results when compared to traditional symbol separation techniques.

1 INTRODUCTION

Code Division Multiple Access (CDMA) is a data transmission technique for the third generation of mobile phones, based on spread spectrum methods. The CDMA system enables users to transmit over the same frequency band simultaneously. The identification of a particular user is done by his unique code.

In the uplink (e.g. base station) signal processing the codes of the users are known but their delays are not known. For delay estimation matched filter [12], subspace approaches [2, 15] or maximum likelihood method [12] can be used. Once the delays are estimated, the other parameters such as the fading process or the symbols can be determined.

The signal processing in the downlink (e.g. mobile phone) differs from that of the uplink. First, only the own code of the mobile phone is known. Second, the mobile phone doesn't have such signal processing capability as the base station. Third, the mathematical model of the channels differs slightly since users share the same channel in the downlink communication.

In this paper our goal is the estimation of the desired user's symbol process. We approach the problem by using blind source separation, which is closely related to Independent Component Analysis(ICA) [6], of a mixture of convolved sources. Independent component analysis (ICA) is a recently developed technique whose goal is to represent a set of random variables as a linear transformation of statistically independent component variables. The unknown linear mixing, as well as the generating independent components can be found by using ICA algorithms that utilize either higher-order moments or time structure of the observed variables.

ICA based approaches for estimating the delays and the fading channel coefficients of the desired user are presented in [8, 14, 13]. In [14] the delay estimation is done by using a fast fixed-point ICA algorithm [7] for computing the basis vectors of the linear transformation, which correspond to shifted versions of the chip sequences of various users. The model is assumed slowly fading. When the channel coefficients are varying, the multiuser access channel can be considered as a mixture of independent signals of normal distributions corresponding to different users. This assumption is used in [13] where a complexity minimization approach is employed for separating the signal envelope and thus the channel coefficients of the desired user.

The model considered in this paper consists of a linear transformation of both the independent variables (the transmitted symbols) and one time unit delayed version of them. A method for separating mixtures of delayed and convolved independent sources is based on the information maximization of the output of the system network [3, 1, 10, 16]. According to our experiments, the proposed method has quite competitive detection capabilities compared with the traditional symbol estimation methods.

2 SIGNAL MODEL

The signal model considered in this paper is a multipath downlink model with slowly fading channel. The data has the form:

$$r(t)=\sum_{m=1}^{N}\sum_{k=1}^{K}b_{km}\sum_{l=1}^{L}a_l s_k(t-mT-d_l)+n(t) \quad (1)$$

where a_l is the fading factor of the lth transmission path, b_{km} is kth user mth symbol, $s_k(\cdot)$ is kth user's chip sequence, $s_k(t)\in\{-1,+1\}, t\in\ [0,T), s_k(t)=0, t\notin[0,T)$, d_l is the delay corresponding to the lth path, which is assumed to be constant during the observation time, and $n(t)$ is the noise. We also assume that there are L transmission paths, and that the fading coefficients corresponding to each path are constant for the given observation interval. The length of the chip sequence is C and N is the number of bits in the observation interval.

We collect C-length column vectors from subsequent discretized equispaced data samples $r[n]$:

$$\mathbf{r}_m=[\ r[mC]\ r[mC+1]\dots r[(m+1)C-1]\ ]^T \quad (2)$$

Equation (2) can further be written with respect to the current symbol vector and the immediately preceding one:

$$\mathbf{r}_m=\sum_{k=1}^{K}[b_{k,m-1}\sum_{l=1}^{L}a_l\underline{\mathbf{g}}_{kl}]+\sum_{k=1}^{K}[b_{km}\sum_{l=1}^{L}a_l\overline{\mathbf{g}}_{kl}]+\mathbf{n}_m \quad (3)$$

where $\mathbf{n}_m$ denotes the noise vector, and the 'early' and 'late' parts of the code vectors are

$$\underline{\mathbf{g}}_{kl}=[\ s_k[C-d_l+1]\dots s_k[C]\ 0\dots 0\ ]^T \quad (4)$$

$$\overline{\mathbf{g}}_{kl}^{L}=[\ 0\dots 0\ s_k[1]\dots s_k[C-d_l]\ ]^T \quad (5)$$

Here d_l is the discretized delay, $d_l\in\{0,\dots,(C-1)/2\}$.

3 FEEDBACK ARCHITECTURE

We express now equation (3) in a more compact form. We define the matrix $\mathbf{R}=[\mathbf{r}_1\dots\mathbf{r}_N]$. It can be represented as

$$\mathbf{r}_m=\mathbf{G}_0\mathbf{b}_m+\mathbf{G}_1\mathbf{b}_{m-1}+\mathbf{n}_m \quad (6)$$

where $\mathbf{G}_0,\mathbf{G}_1$ are $C\times K$ mixing matrices corresponding to the original and the one time unit delayed symbols. The column vectors of $\mathbf{G_0}$ and $\mathbf{G_1}$ are given by the 'early', respectively 'late' parts of the coding vectors:

$$\mathbf{G}_0=[\sum_{l=1}^{L}a_l\underline{\mathbf{g}}_{1l},\dots,\sum_{l=1}^{L}a_l\underline{\mathbf{g}}_{Kl}] \quad (7)$$

$$\mathbf{G}_1=[\sum_{l=1}^{L}a_l\overline{\mathbf{g}}_{1l},\dots,\sum_{l=1}^{L}a_l\overline{\mathbf{g}}_{Kl}] \quad (8)$$

We notice from equation (6) that our signal model can be regarded as a linear mixture of delayed and convolved sources, in the particular case when the maximum delay is one time unit. If we consider that none of the mixing matrices (i.e. users codes) or symbol sequences is known, then we are in the framework of blind source separation (BSS) [4, 9, 11]. One method for solving this convolved mixtures BSS problem is by considering a feedback architecture. Since we suppose the users to be independent, then we may employ for the task of source separation the maximization of the entropy of a nonlinear function of the output, and optimize the weights of the network using the natural gradient algorithm [3, 1, 10, 16]. The proposed architecture is shown in figure 1.

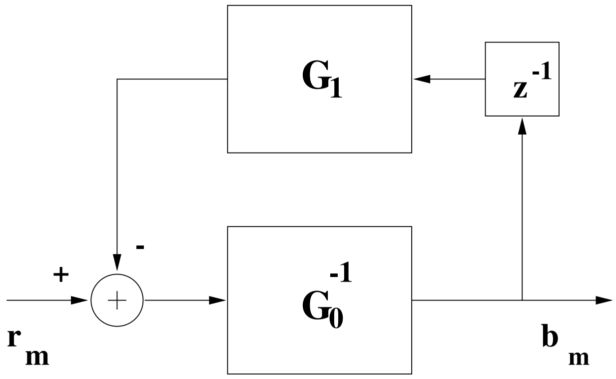

Figure 1: A feedback network for CDMA detection

A common preprocessing step in ICA and BSS is whitening of the input data $\mathbf{r}_m$, which removes as much as possible of the second order statistic effects and filters some additive noise. In the whitening step we also reduce the dimension to K (the number of users) since this is the actual number of independent components. The new data is then of the form

$$\mathbf{V}=\mathbf{\Lambda}_s^{-\frac{1}{2}}\mathbf{U}_s^T\mathbf{R} \quad (9)$$

where $\mathbf{\Lambda}_s$ and $\mathbf{U}_s$ corresponds to the K eigenvalues and eigenvectors of the correlation matrix estimate $\mathbf{R}\mathbf{R}^T/(N-1)$, respectively.

Then we may write the whitened version of equation (6):

$$\mathbf{v}_m=\mathbf{A}_0\mathbf{b}_m+\mathbf{A}_1\mathbf{b}_{m-1} \quad (10)$$

where $\mathbf{v}_m$ is the whitened input vector, and $\mathbf{A}_{0,1}$ are the whitened square matrices of dimension K. Now we express the vector of symbols $\mathbf{b}_m$ as a function of the received whitened mixture $\mathbf{v}_m$ and the previously estimated vector of symbols $\mathbf{b}_{m-1}$

$$\mathbf{b}_m=\mathbf{A}_0^{-1}(\mathbf{v}_m-\mathbf{A}_1\mathbf{b}_{m-1}) \quad (11)$$

where $\mathbf{v}_m$ is the whitened input vector, and $\mathbf{A}_0,\mathbf{A}_1$ are the whitened square mixing matrices of dimension K.

4 DETECTION ALGORITHMS

Based on this feedback architecture we propose the following algorithm for blind symbol detection in a CDMA system:

1. Initialize randomly $\mathbf{A}_{0,1}$
2. Use the following update rules for the mixing matrices [3, 10].

$$\Delta\mathbf{A}_0 = -\mathbf{A}_0(\mathbf{I} + \mathbf{y}_m\mathbf{b}_m^T) \quad (12)$$
$$\Delta\mathbf{A}_1 = -(\mathbf{I} + \mathbf{A}_1)\mathbf{y}_m\mathbf{b}_{m-1}^T \quad (13)$$

where $\mathbf{y}_m = f(\mathbf{b}_m)$ is applied elementwise and f is an appropriate nonlinearity function.

3. Update the system using the following equations

$$\mathbf{A}_{0,1} = \mathbf{A}_{0,1} + \mu\Delta\mathbf{A}_{0,1} \quad (14)$$

4. Compute $\mathbf{b}_m$ as in equation (11)
5. If $\mathbf{A}_{0,1}$ have not converged, go to step 2.
6. Apply **sign** nonlinearity on the final estimated value of $\mathbf{b}_m$
7. Identify the desired user's symbol sequence which best fits the training sequence.

The identity matrix of size K is denoted here by $\mathbf{I}$. If some information about the delays of transmission of the desired user is available, it may be used in the initialization of step 1. The updating rules of step 2 follow the rules of the algorithms described in [10, 16] in the case when only a delay of one time unit mixes with the current time vector of symbols. Since the system has feedback the choosing of the learning rate μ in step 4 is essential for the convergence. We used a constant rate, but some iteration dependent strategy may improve the convergence time. Convergence in step 5 is verified by the mean-square-error matrix norm. Since the transmission system is binary differential, step 6 provides the most probable value for the estimated symbol. The detector estimates all users symbols upto a permutation, that is why the pilot sequence in step 7 is needed to identify the desired user.

We compared our method with the standard algorithms used in multiuser detection, Minimum Mean-Square-Error (MMSE) and Matched Filter (MF). The MF estimator is simply

$$b_{MMSE} = \mathbf{g_1}^T\mathbf{R} \quad (15)$$

and the MMSE symbol estimator is given by

$$b_{MMSE} = \mathbf{g_1}^T\mathbf{U}_s\mathbf{\Lambda}_s^{-1}\mathbf{U}_s^T\mathbf{R} \quad (16)$$

with $\mathbf{\Lambda_s}, \mathbf{U_s}$ expressed earlier and $\mathbf{g}_1$ the desired user chip sequence.

5 SIMULATIONS

The algorithms were tested using quasi orthogonal gold codes of length $C = 31$. The number of users was $K = 4$ and $K = 4$ and the number of transmission paths was $L = 3$. The channel paths powers were $-5, -5$ and $0dB$ respectively, for every user and the signal-to-noise ratio was varied from $30dB$ to $0dB$, with respect to the main

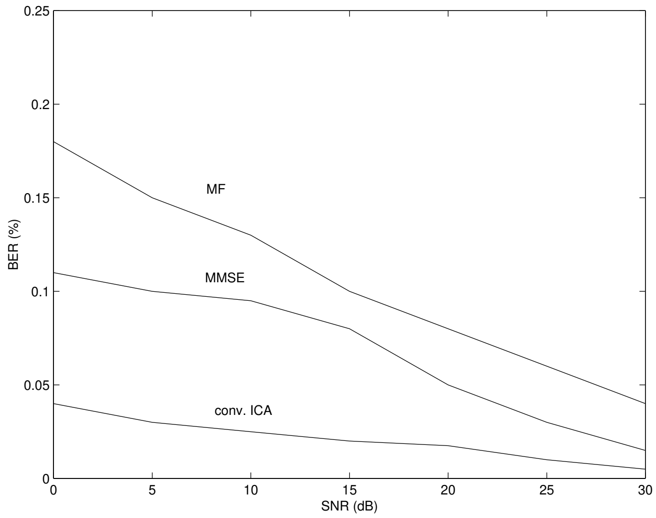

Figure 2: BER for convolutive mixture ICA, MMSE and MF algorithms, respectively. Number of users $K = 4$ and $\mu = 0.05$

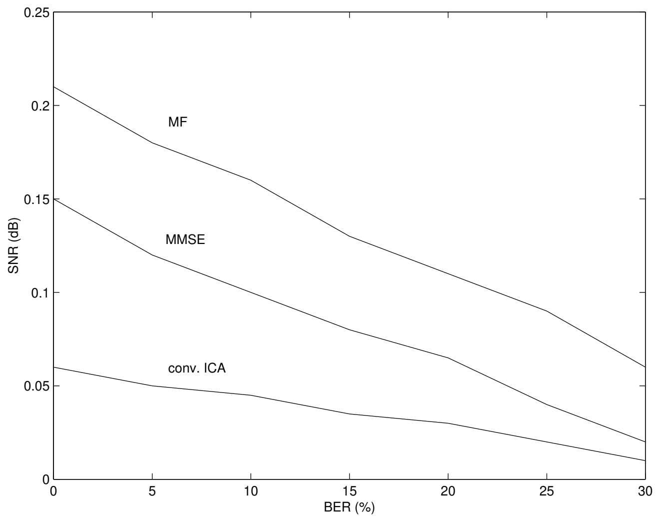

Figure 3: BER for convolutive mixture ICA, MMSE and MF algorithms, respectively. Number of users $K = 8$ and $\mu = 0.05$

path. Only the real part of the data was used. The observation interval was $N = 500$. A training sequence of length $P = 20$ was compared to the preamble of the separated sources, in order to identify the desired user. A constant learning rate $\mu = 0.05$ was used. Convergence was achieved in around 20 iterations for such environmental conditions. Experiments bit-error-rate (BER) results in figures 2,3 show that our method yields better separation results than the compared algorithms.

6 CONCLUSIONS

In this paper we have introduced a new algorithm for symbol detection in a CDMA system based on a feedback architecture approach of the blind source separation of mixed and convolved sources. Although we used a batch version, a sequential approach makes it suitable for adaptive estimation as well. Our simulations show that the new approach performs better than the well-known MF and MMSE algorithms. Standard methods don't take into account the reasonable assumption of independent signal sources that is supposed in our method. An advantage with the batch approach we presented is that in the estimation of the current symbol vector, two observation columns are used, thus improving the estimation. Also, no need of synchronization is needed as in the case of MMSE and MF since the different users path delays are estimated simultaneously implicitly in the basis vectors of the mixing matrices.

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